Observations of EUV spectra from highly charged heavy ions in optically thin plasmas for benchmarking models

Chihiro Suzuki[1], Fumihiro Koike[2], Izumi Murakami[1], Naoki Tamura[1], Shigeru Sudo[1], T. Higashiguchi[3], G. O'Sullivan[4]

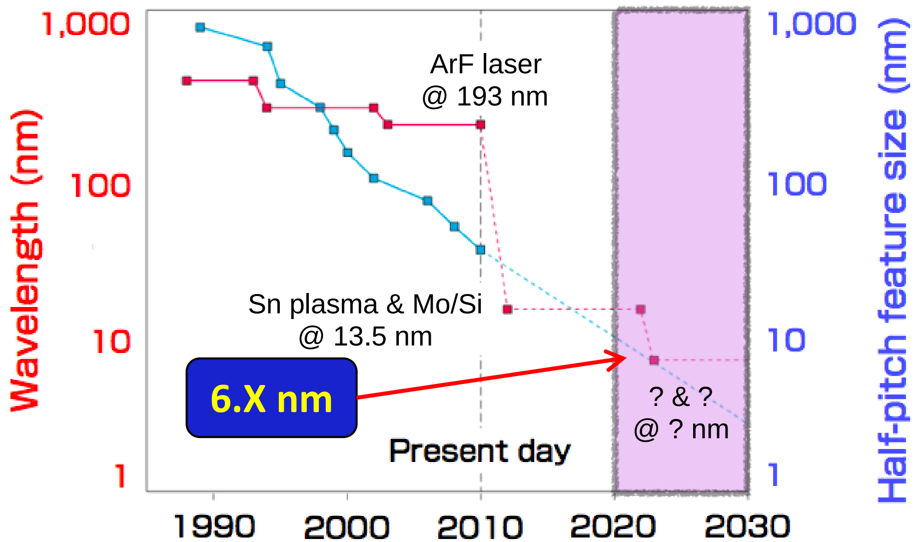
[1]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[2]Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo 102-8554, Japan
[3]Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan
[4]University College Dublin, Belfield, Dublin 4, Ireland

Outline

- Heavy ions applicable to BEUV light sources
  - For lithography & biological microscopy
- EUV spectroscopy in optically thin plasmas
  - LHD — a magnetically confined fusion device
  - Benefits for benchmarking models
- EUV spectra of lanthanides (e.g., Gd)
  - Temperature dependence
  - Identifications & interpretations
- Z dependence of EUV spectra
  - Comparisons with LPPs and calculations

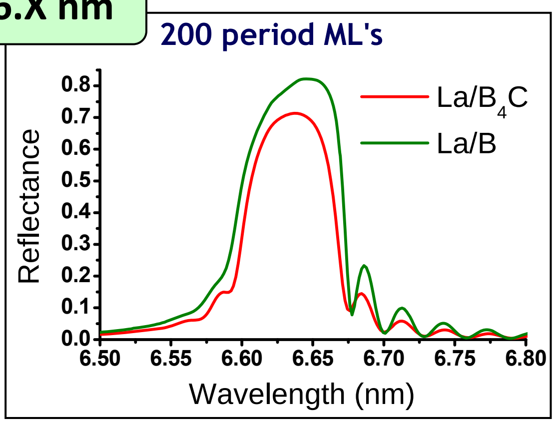
Beyond EUV sources using lanthanides ?

Trend of LSI feature size



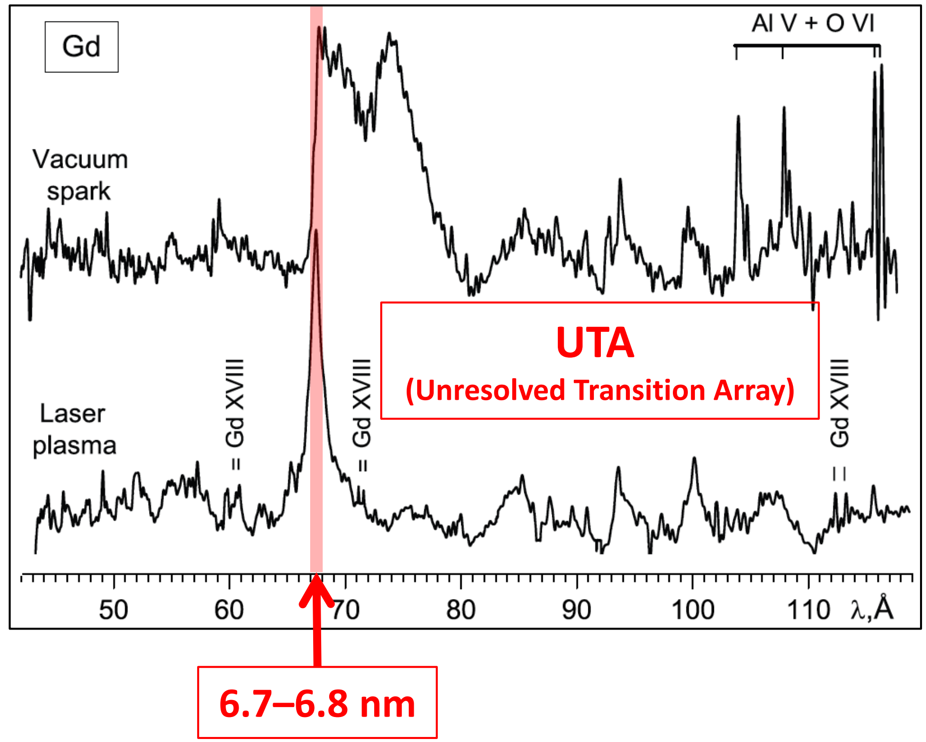
G. Tallents et al., Nature Photonics **4**, 809 (2010).

MLM near 6.X nm



E. Louis et al., EUV Source Workshop (2011).

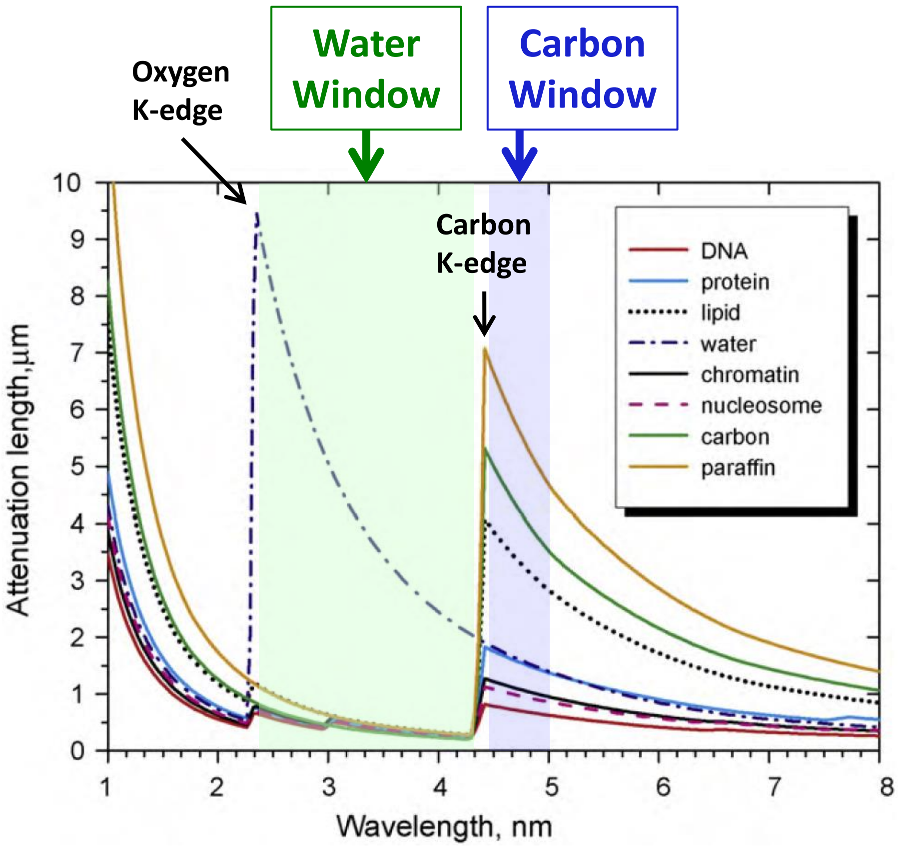
UTA features of gadolinium near 6.X nm



S S Churilov et al., Phys. Scr. **80**, 045303 (2009).

Biological microscopy in water window & carbon window

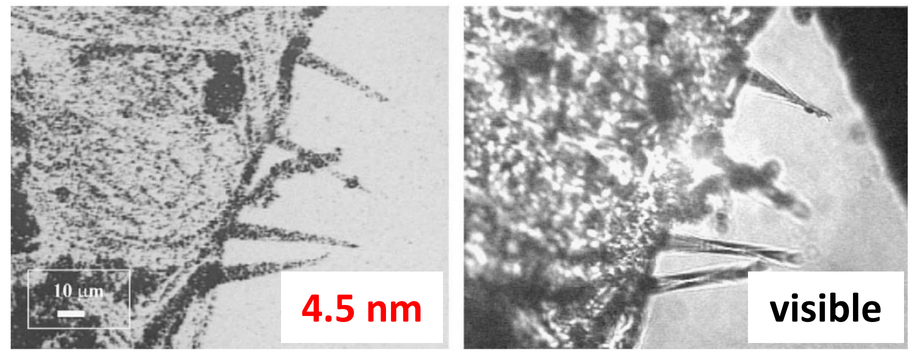
Transparencies of biological materials



I.A. Artyukov et al., Micron **41**, 722 (2010).

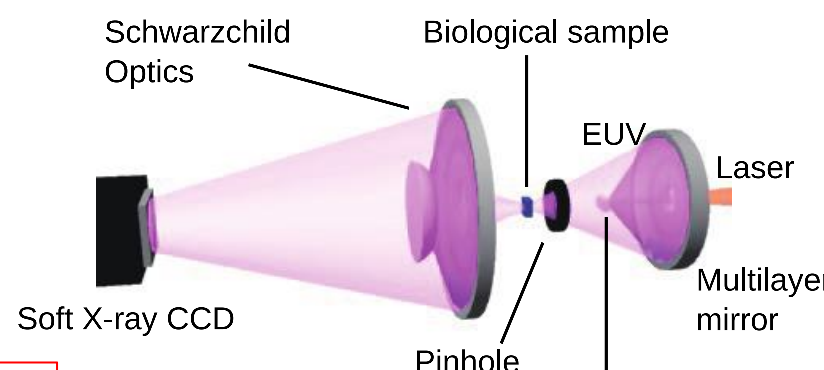
Sample image in carbon window

(bush-cricket wing)



I.A. Artyukov et al., Micron **41**, 722 (2010).

Proposed optics for soft X-ray microscopy

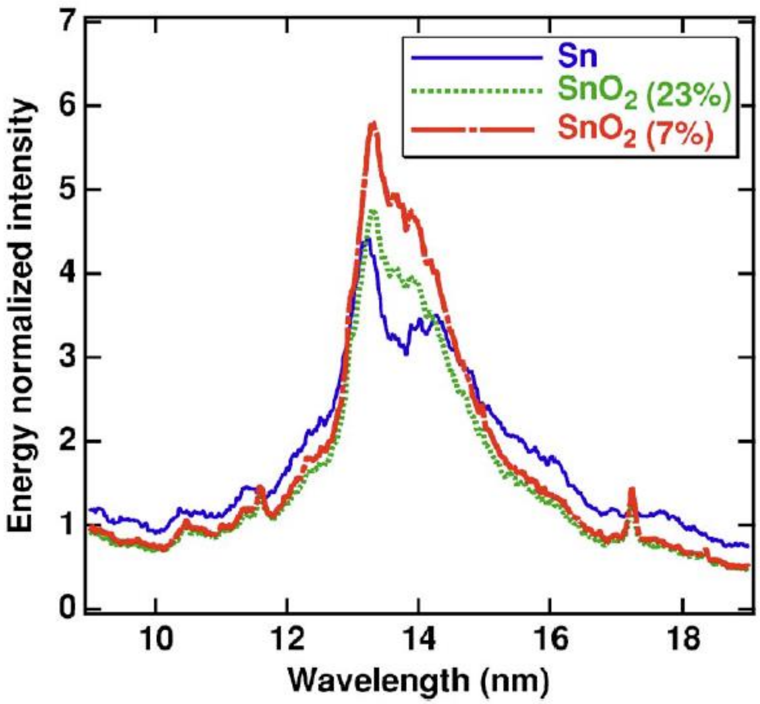


LPP of Au, Pb, Bi, ... ?

T. Higashiguchi et al., Appl. Phys. Lett. **100**, 014103 (2012).

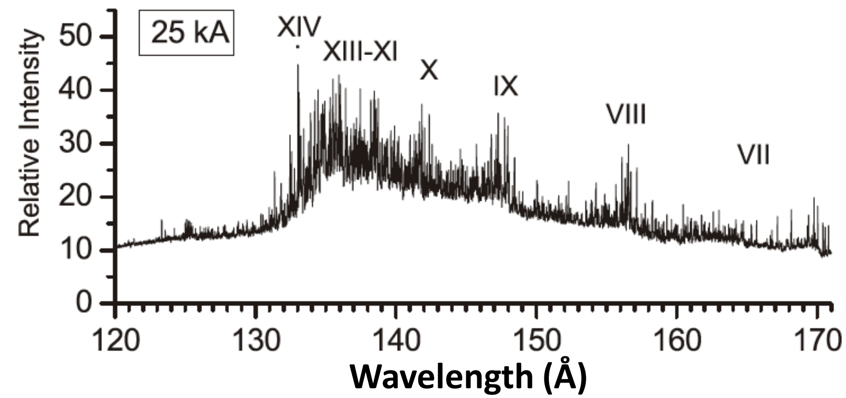
EUV spectra of tin in optically thick/thin plasmas

LPP



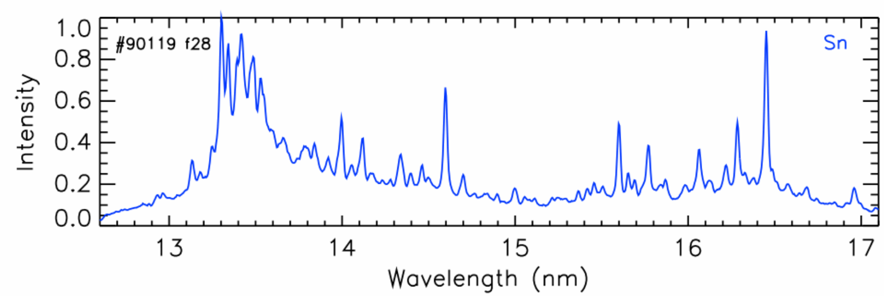
T. Okuno et al., Appl. Phys. Lett. **88**, 161501 (2006).

Vacuum spark



S. S. Churilov and A. N. Ryabtsev, Phys. Scr. **73**, 614 (2006).

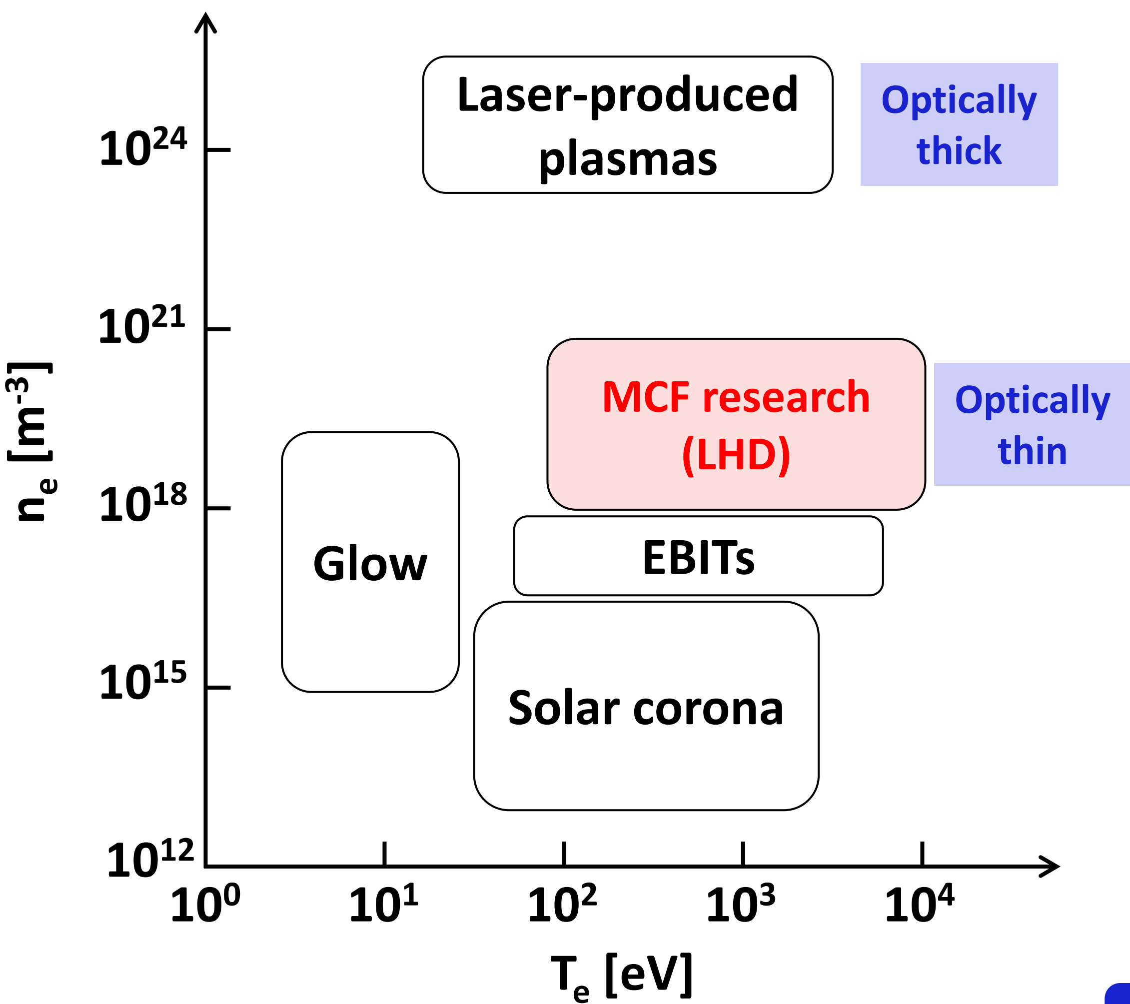
Optically thin plasma (LHD)



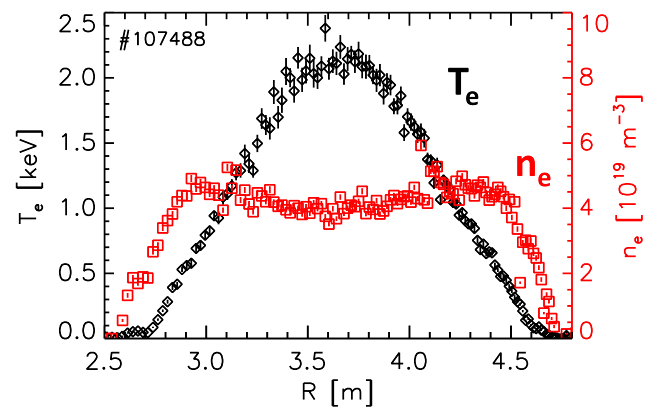
C. Suzuki et al., J. Phys. B **43**, 074027 (2010).

- **Higher opacity and small scale length in LPP**
  - **Sometimes more difficult to benchmark with models**

Why experiment in magnetically confined fusion (MCF) device?



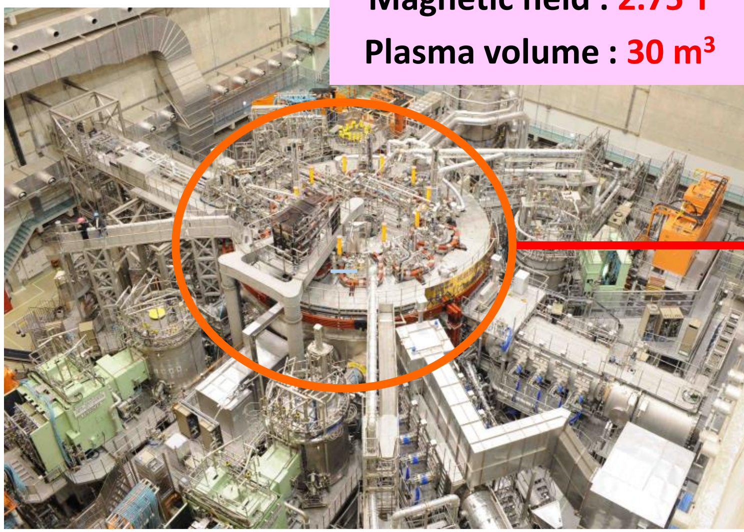
- Simple spectrum without large absorption/broadening
- Controllable T_e and n_e in wide ranges
- Direct/precise measurements of T_e and n_e without modeling

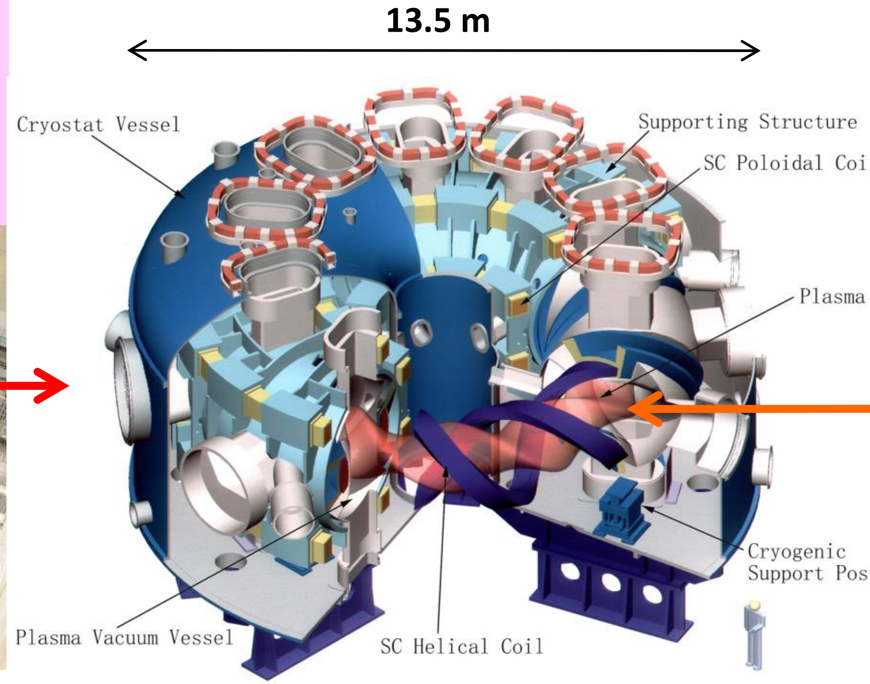


Suitable for benchmarking models

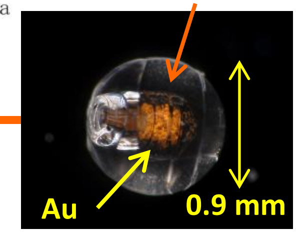
Large Helical Device (LHD)

Major radius : 3.9 m
Minor radius : 0.6 m
Magnetic field : 2.75 T
Plasma volume : 30 m^3





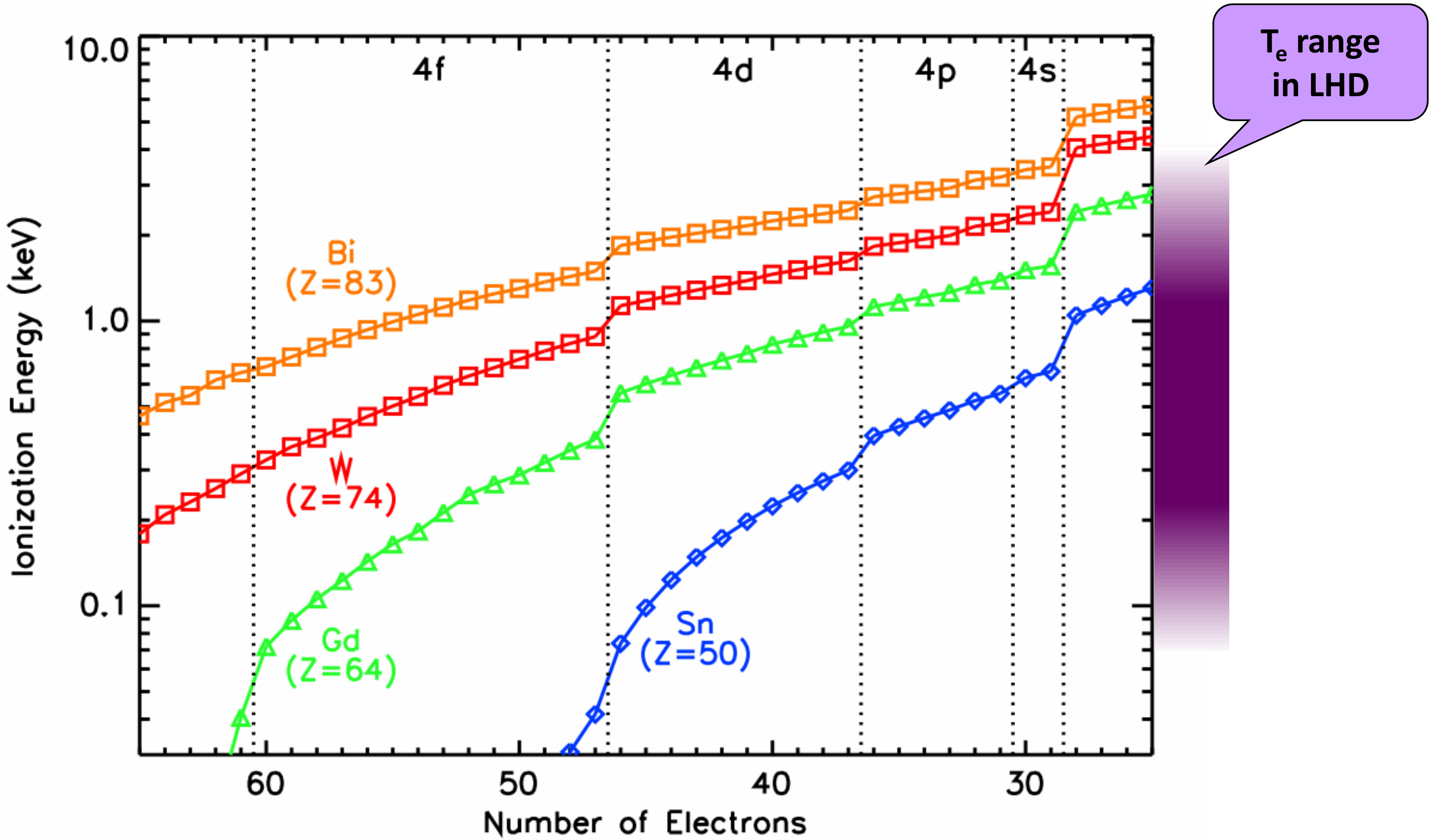
Polystyrene $(C_8H_8)_n$



Tracer encapsulated solid pellet

- Large-scale facility for MCF at the National Institute for Fusion Science (NIFS)
- High temperature (keV order) and low density (n_e = 10^{18}~10^{20} m^{-3}) plasmas are routinely produced in large volume (30 m^3).
- Tracer encapsulated solid pellet (TESPEL) injection system is available.
- Highly charged heavy ions can be easily generated in optically thin conditions.

Ion stages mainly observed in LHD



Contribution of open *N* shell (n=4) ions are commonly important in these high Z elements

General spectral feature of open N shell ions

Ion Charge

# of Electrons

# of electrons	Iso. sequence	Ground State Configuration								
		M	N				O			P
		3d	4s	4p	4d	4f	5s	5p	5d	6s
28	Ni	10								
29	Cu	10	1							
30	Zn	10	2							
31	Ga	10	2	1						
32	Ge	10	2	2						
33	As	10	2	3						
34	Se	10	2	4						
35	Br	10	2	5						
36	Kr	10	2	6						
37	Rb	10	2	6	1					
38	Sr	10	2	6	2					
39	Y	10	2	6	3					
40	Zr	10	2	6	4					
41	Nb	10	2	6	5					
42	Mo	10	2	6	6					
43	Tc	10	2	6	7					
44	Ru	10	2	6	8					
45	Rh	10	2	6	9					
46	Pd	10	2	6	10					
47	Ag	10	2	6	10	1				
48	Cd	10	2	6	10	2				
49	In	10	2	6	10	3				
50	Sn	10	2	6	10	4				
51	Sb	10	2	6	10	5				
52	Te	10	2	6	10	6				
53	I	10	2	6	10	7				
54	Xe	10	2	6	10	8				
55	Cs	10	2	6	10	9				
56	Ba	10	2	6	10	10				
57	La	10	2	6	10	11				
58	Ce	10	2	6	10	11	1			
59	Pr	10	2	6	10	11	2			
60	Nd	10	2	6	10	12	2			
61	Pm	10	2	6	10	13	2			
62	Sm	10	2	6	10	14	2			
63	Eu	10	2	6	10	13	2	2		

Open 4s/4p ions

Smaller number of energy levels in subshells
Discrete line spectral feature

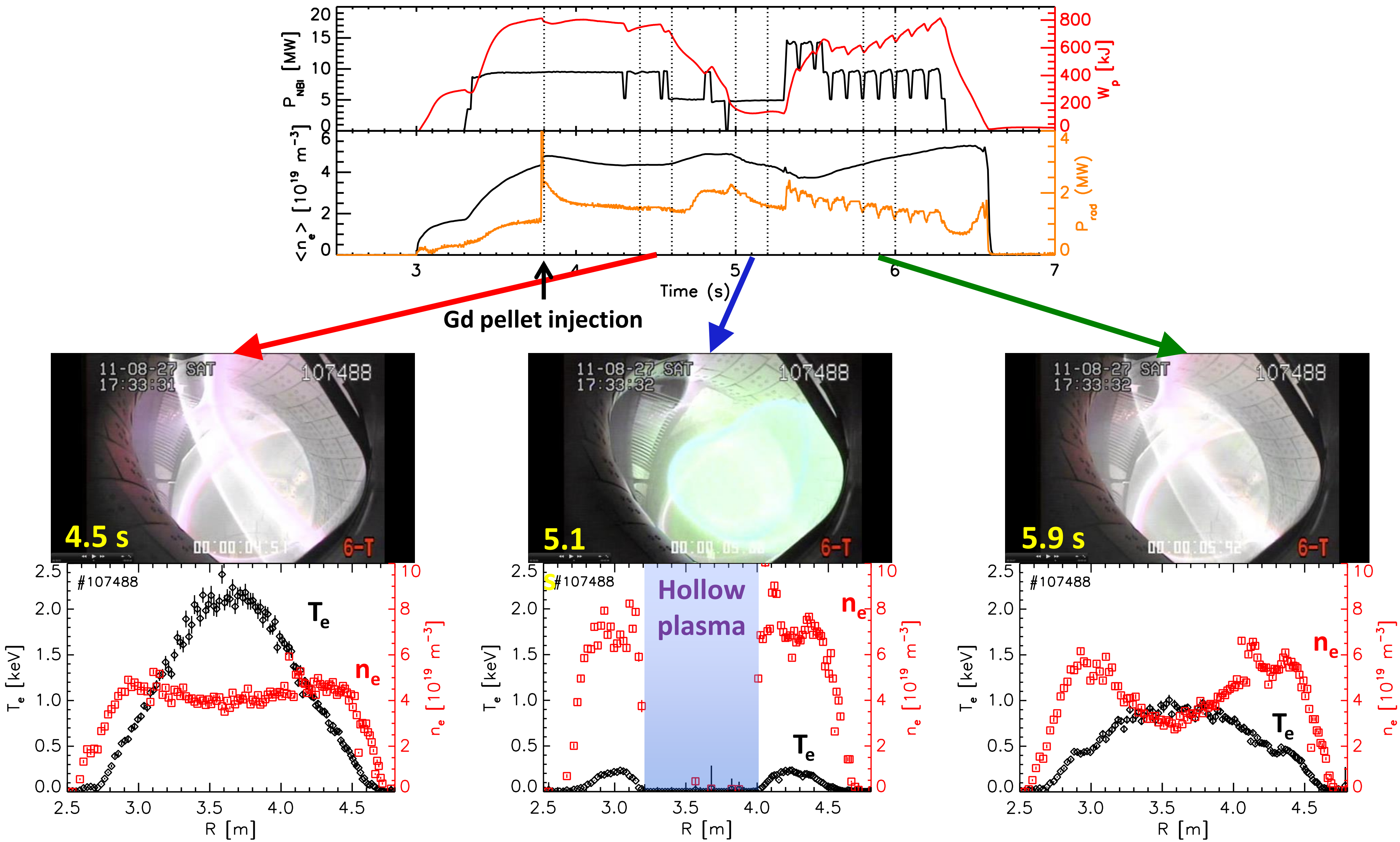
Open (partially filled) 4d ions [$4p^6 4d^k$]

Larger number of energy levels in subshells
Quasicontinuum UTA feature

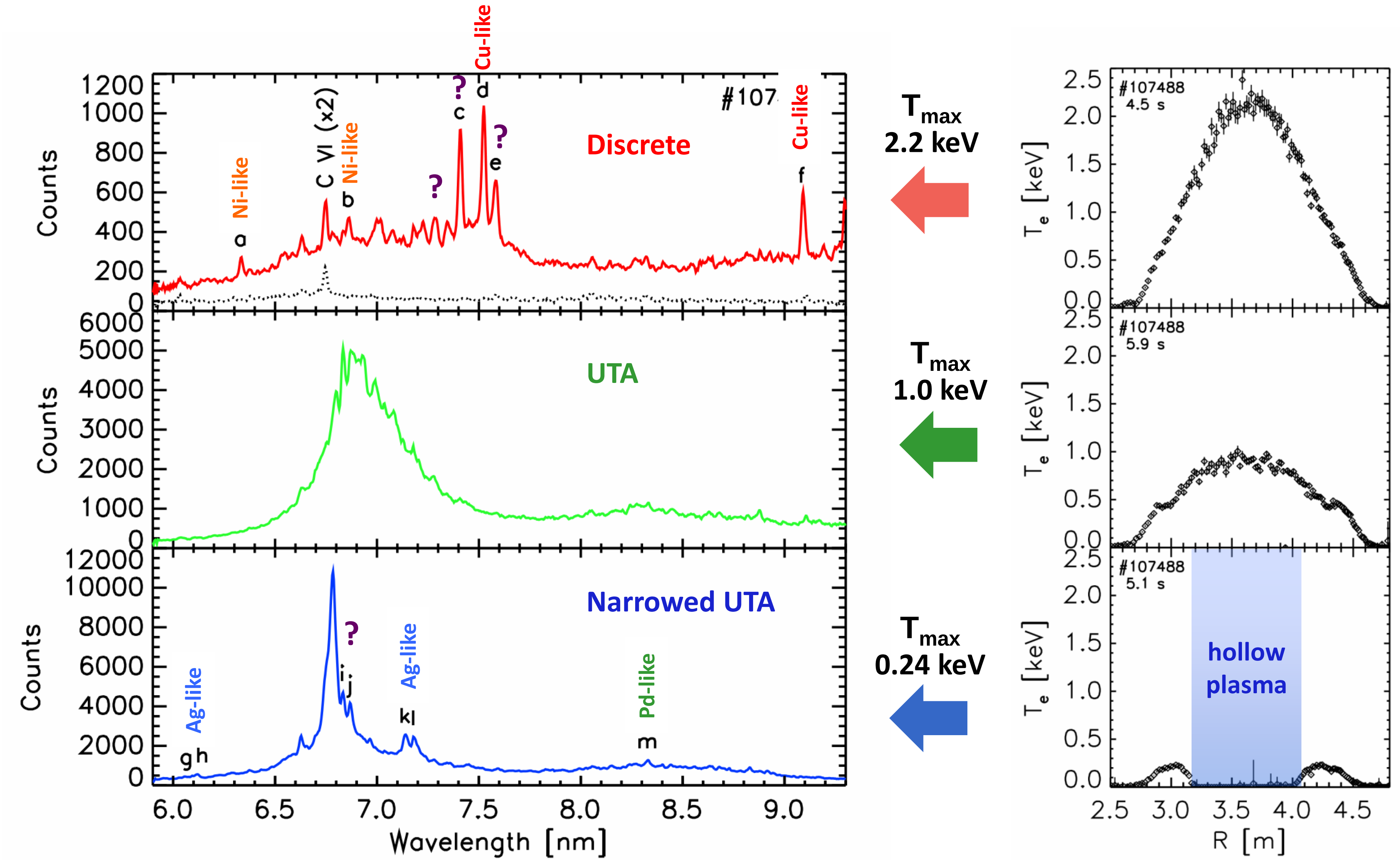
Open (partially filled) 4f ions [$4d^{10} 4f^k$]

Huge number of energy levels
More complex UTA feature

LHD discharge with Gd (Z=64) pellet injection



Different EUV spectra from Gd ions in LHD



C. Suzuki et al., J. Phys. B: At. Mol. Opt. Phys. **45**, 135002 (2012).

Calculation of unknown lines by Hullac and Grasp code

Measured wavelength (nm)	Calculated wavelength (nm)	Ion	Transition	Previous works
7.279	7.268 (H) 7.168 (G)	Gd XXXIII (Ge-like)	$4s^2 4p^2{}_2 - 4s^2 4p4d_1$	
	7.279 (H) 7.288 (G)	Gd XXXIV (Ga-like)	$4s^2 4p_{1/2} - 4s^2 4d_{3/2}$	7.41 (Exp.) [1] 7.326 (Theory)
7.409	7.406 (H) 7.411 (G)	Gd XXXV (Zn-like)	$4s4p_1$-$4s4d_2$	
7.524	7.522 (H) 7.528 (G)	Gd XXXVI (Cu-like)	$4p_{1/2}$-$4d_{3/2}$	7.5259 (Exp.) [2]
7.583		?		

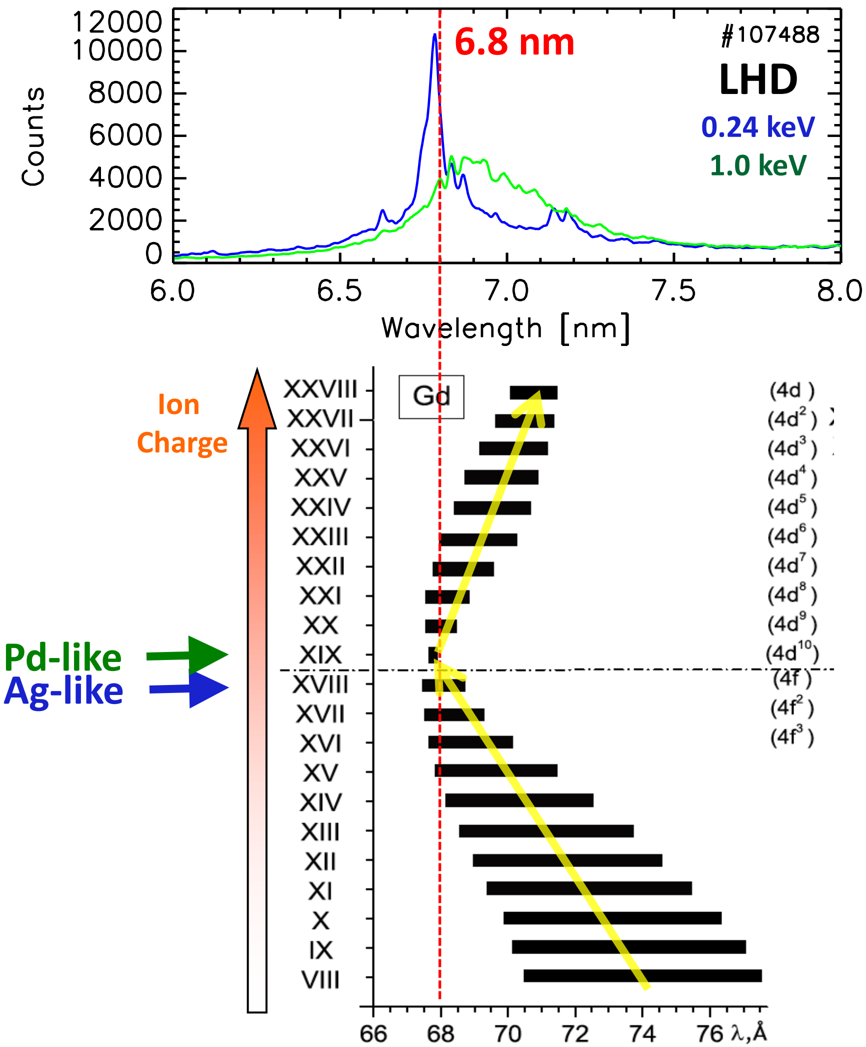
H: Calculated by Hullac

G: Calculated by Grasp

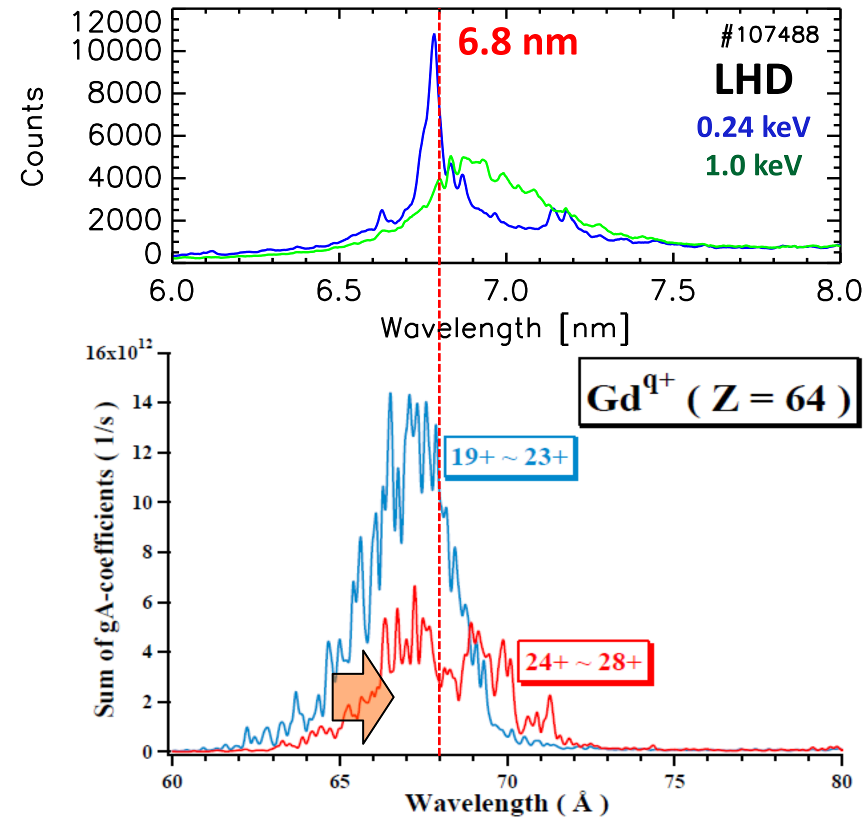
[1] Fournier et al., Phys. Rev. A **50**, 2248 (1994). exp. in TEXT tokamak

[2] Doschek et al., J. Opt. Soc. Am. B **5**, 243 (1988). exp. in LPP

Comparison of UTA features with calculations



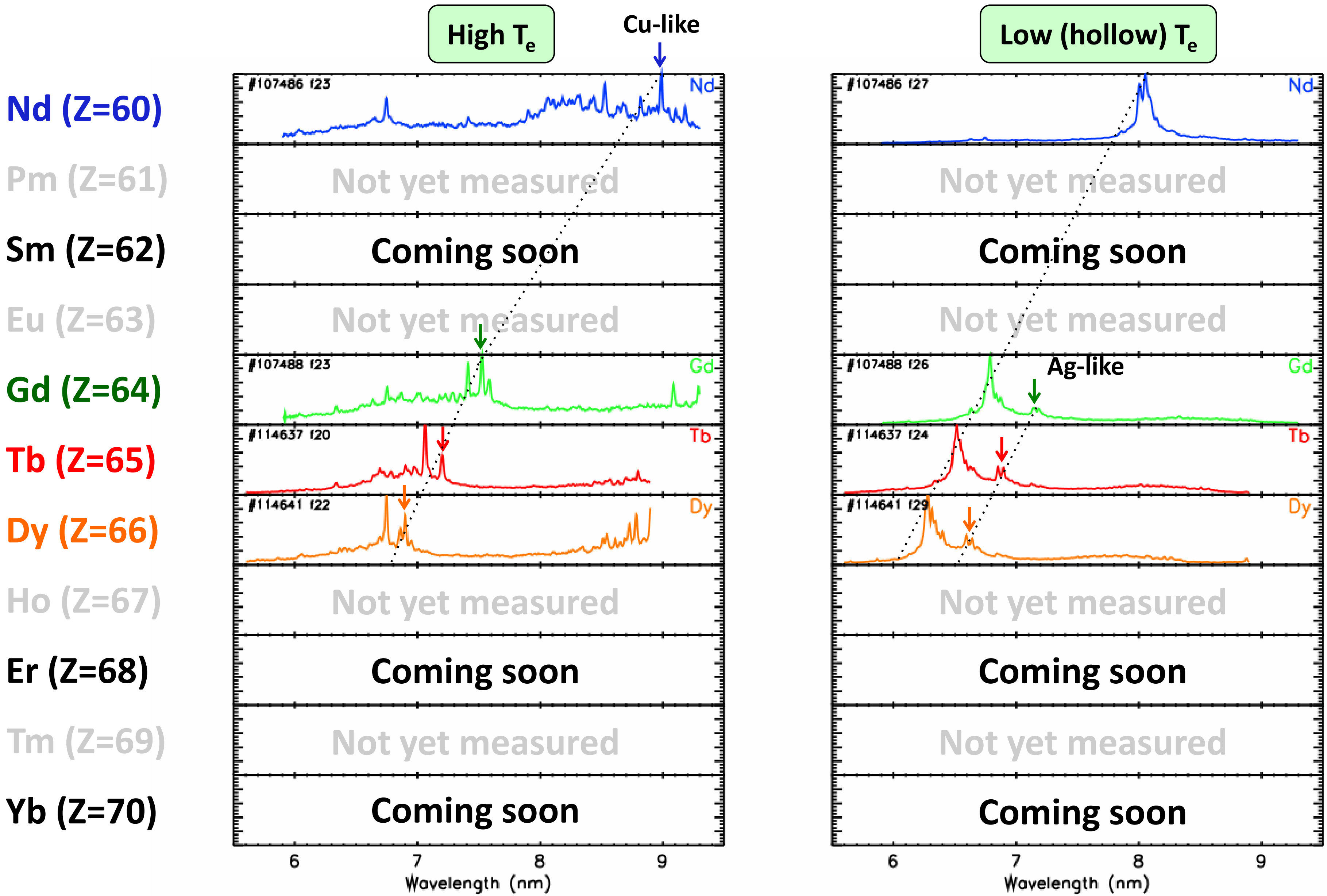
Spectral bands of Gd ions
(by Cowan's code with CI)
S. S. Churilov et al., Phys. Scr. **80**, 045303 (2009).



Synthesized spectra of Gd ions
(by Grasp code with CI)
F. Koike et al., Phys. Scr. **T156**, 014079 (2013).

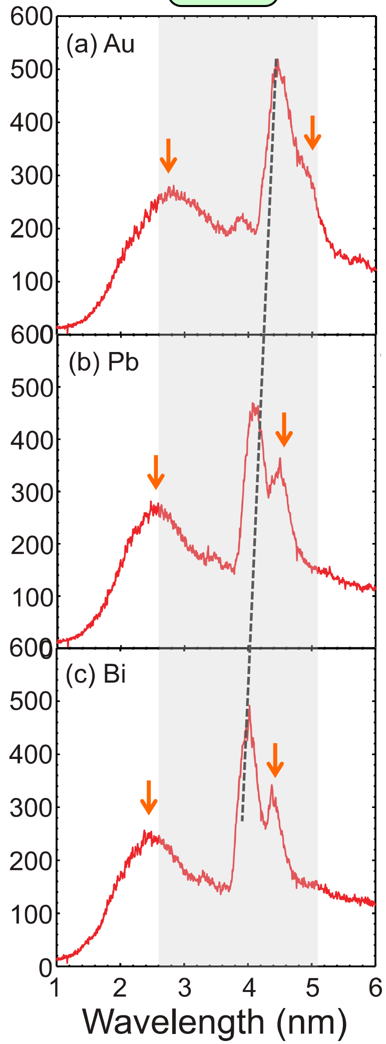
Construction of collisional-radiative modeling should be necessary for detailed analyses .

Z dependence of the lanthanides spectral appearance in LHD

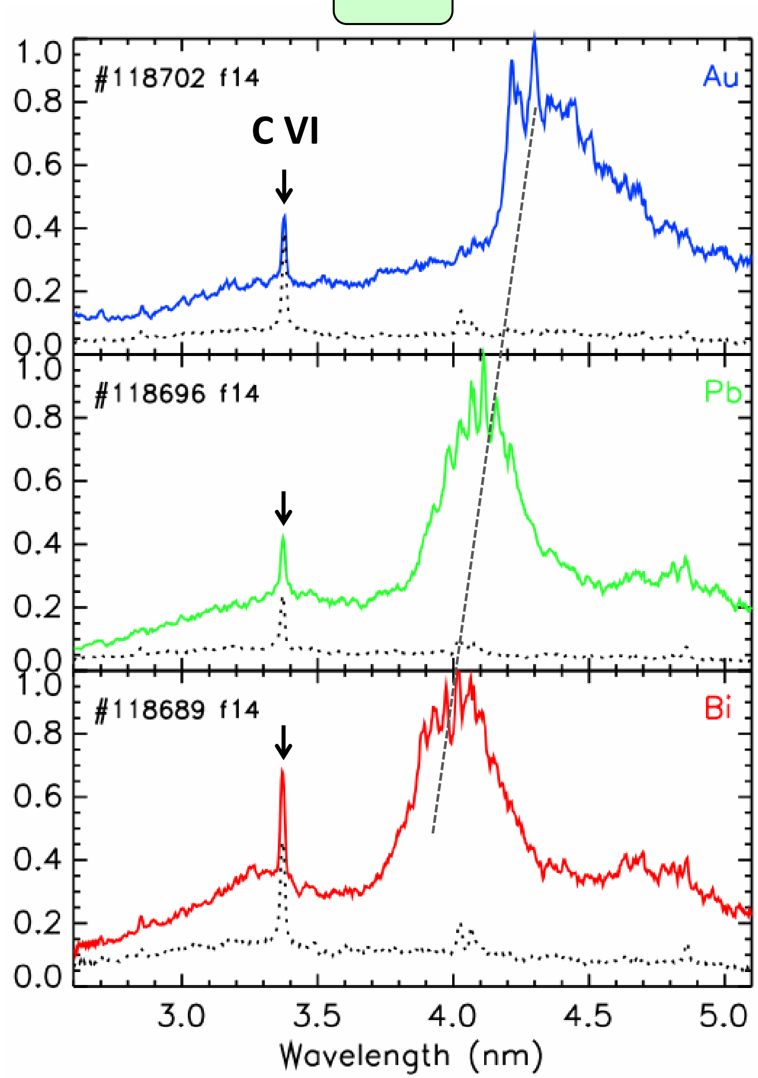


Z dependence of Au–Bi in LPP and LHD

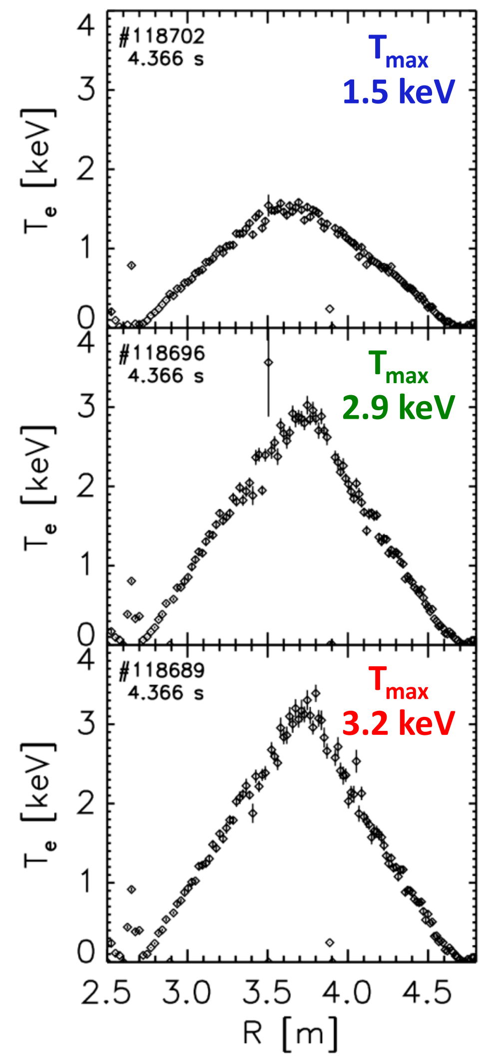
LPP



LHD



T_e in LHD



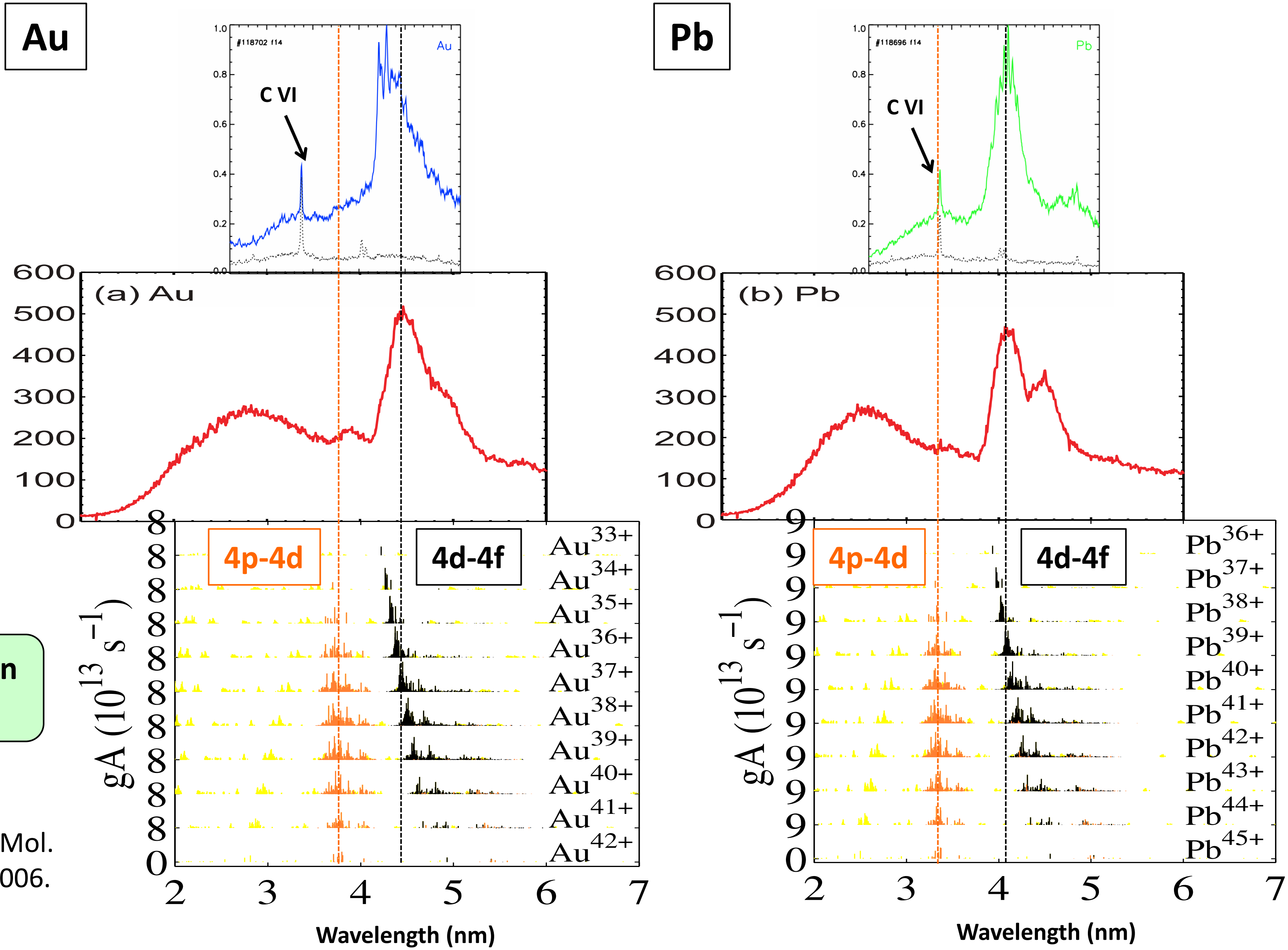
T. Higashiguchi et al., Appl. Phys. Lett. **100**, 014103 (2012).

Comparisons with FAC code calculation

LHD

LPP

FAC code calculation
for 4d ions



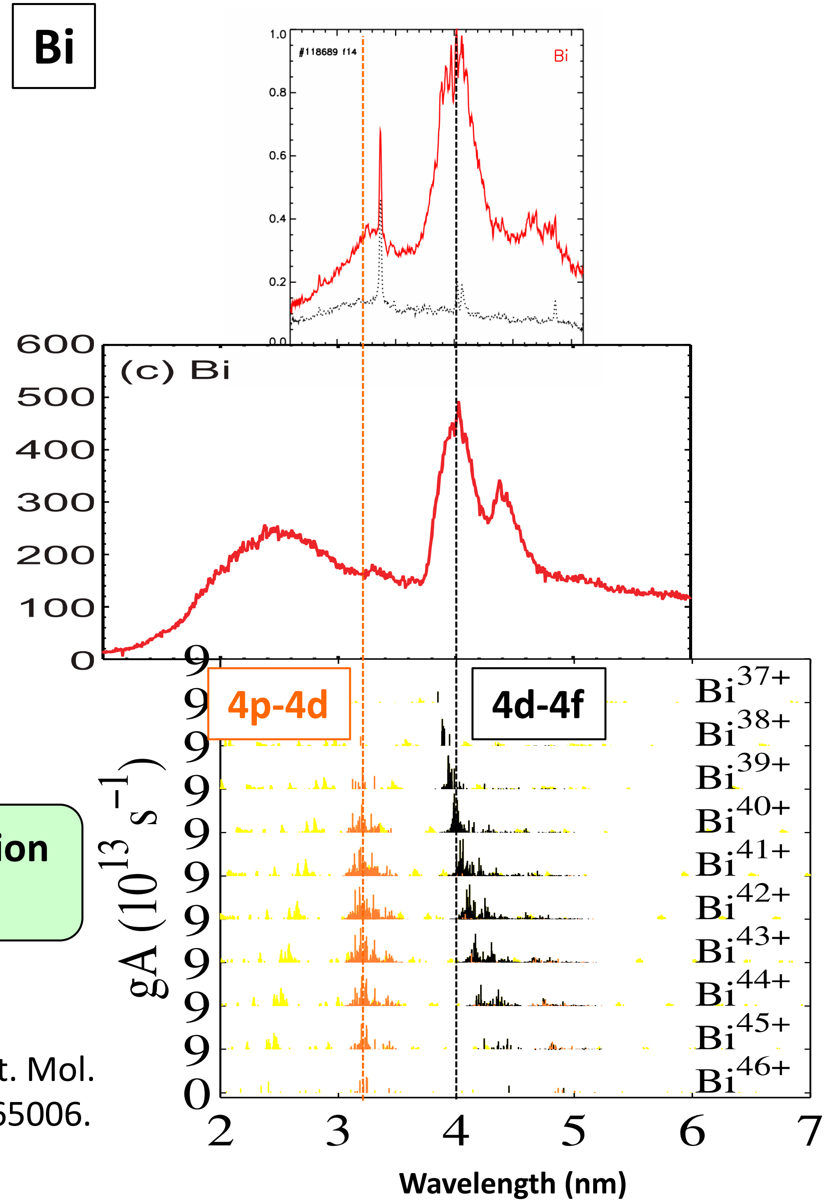
D. Kilbane, J. Phys. B: At. Mol. Opt. Phys. **44** (2011) 165006.

Comparisons with FAC code calculation (contd.)

LHD

LPP

FAC code calculation for 4d ions



D. Kilbane, J. Phys. B: At. Mol. Opt. Phys. **44** (2011) 165006.

- The UTAs from open 4f ions observed in LPP are missing in LHD.
- The spectra of 4p-4d transitions are weak or missing in LHD and LPP.

Differnce in excitation process ?

Summary

- **EUV spectroscopy in optically thin plasmas such as LHD is a good experimental platform for benchmarking models of highly charged heavy ions relevant to the applications to EUV lithography and biological microscopy.**

- **We have measured discrete and narrowed UTA features of EUV spectra from lanthanide ions in LHD plasmas following the change in electron temperature.**

- **We have also observed Z depenence of EUV spectra from lanthanides to bismuth ions, and comparative analyses with LPPs and theoretical models have got started.**